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ON V/STOL HANDLING CHARACTERISTICS BASED

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SUMMARY

A flight investigation utilizing a variable-stability helicopter was conducted in order to determine the effects of gross changes in static directional stability on V/STOL handling qualities and on requirements for directional sensitivity and damping during low-speed operation. Tasks under both simulated instrument and visual conditions were used for evaluation of the handling characteristics provided by various combinations of static directional stability, directional sensitivity and damping, and dihedral effect.

The results indicate that increases in static directional stability, when accompanied by appropriate increases in directional damping, yield improved handling qualities. Minimum satisfactory levels of directional sensitivity and damping correspond to current crite[illegible]

INTRODUCTION

The full potential of V/STOL aircraft cannot be realized until routine operation at low forward speeds can be achieved under instrument flight rules (IFR), as well as under visual flight rules (VFR). Low-speed capability is essential to the execution of steep approaches from consideration of both rate-of-descent limitations and ground-run distances following landing. The rapid deterioration in handling qualities as operating speeds are reduced necessitates definition of the problems involved.

The purpose of the present investigation was to determine the effects of gross changes in static directional stability on handling qualities, as well as on requirements for directional sensitivity and damping. (The term "sensitivity" as used herein is defined as initial angular acceleration per unit control input; this usage is in conformity with the usage of reference 1 and replaces the term "ratio of control power to inertia" used in refs. 2 and 3.) Current criteria with respect to sensitivity and damping (see ref. 2) are based on studies which employed a helicopter with an inherently high level of static directional stability (ref. 3).

The current investigation employed a variable-stability helicopter with which both instrument and visual flights were conducted. During the tests, pilot ratings and comments and aircraft time histories were obtained for various combinations of static directional stability, directional sensitivity, directional damping, and dihedral effect.

Three NASA research test pilots and one U.S. Army research pilot participated in the investigation.

SYMBOLS

M_{X_δ} rolling moment per unit of stick deflection, lb-ft/in.

M_{X_p} rolling moment proportional to rolling velocity (stable when negative, thus damping in roll), $\frac{\text{lb-ft}}{\text{radian/sec}}$

M_{X_v} rolling moment proportional to side component of velocity thus dihedral effect (stable when negative), $\frac{\text{lb-ft}}{\text{ft/sec}}$

M_{Z_δ} yawing moment per unit pedal travel, lb-ft/in.

M_{Z_r} yawing moment proportional to yawing velocity (stable when negative, thus damping in yaw), $\frac{\text{lb-ft}}{\text{radian/sec}}$

M_{Z_β} yawing moment proportional to sideslip angle (stable when positive), $\frac{\text{lb-ft}}{\text{radian}}$

M_{Y_δ} pitching moment per unit stick deflection, $\frac{\text{lb-ft}}{\text{in.}}$

M_{Y_q} pitching moment proportional to pitching velocity (stable when negative, thus damping in pitch), $\frac{\text{lb-ft}}{\text{radian/sec}}$

I_X moment of inertia about the body X-axis, slug-ft^2

I_Y moment of inertia about the body Y-axis, slug-ft^2

I_Z moment of inertia about the body Z-axis, slug-ft^2

M_{Y_u} pitching moment proportional to forward velocity component, $\frac{\text{ft-lb}}{\text{ft/sec}}$

M_{Y_α} pitching moment proportional to angle of attack, $\frac{\text{ft-lb}}{\text{radian}}$

ζ damping ratio defined as $\dfrac{M_{Z_r}/I_Z}{2\sqrt{M_{Z_\beta}/I_Z}}$

p rolling angular velocity, radian/sec

$\dot{p}$ rolling angular acceleration, radian/sec^2

r yawing angular velocity, radian/sec

$\dot{r}$ yawing angular acceleration, radian/sec^2

β angle of sideslip, radian

$\dot{\beta}$ time rate of change of sideslip angle, radian/sec

δ_X lateral stick deflection, in.

δ_Z pedal deflection, in.

V resultant velocity, ft/sec

v side component of velocity, ft/sec

EQUIPMENT AND SIMULATION TECHNIQUE

The variable-stability helicopter, shown in figure 1, was employed in the simulation. A detailed description of the variable-stability system and the computer-model simulation technique is given in reference 4.

The function of analog computing equipment, into which the simulated dynamics are programed, is illustrated in figure 2. The following equations, which were programed into the computer, defined the directional and lateral dynamics:

$$\dot{r} = \frac{M_{Z_\delta}}{I_Z}\delta_Z + \frac{M_{Z_r}}{I_Z}r + \frac{M_{Z_\beta}}{I_Z}\beta$$

$$\dot{p} = \frac{M_{X_\delta}}{I_X}\delta_X + \frac{M_{X_p}}{I_X}p + \frac{M_{X_v}}{I_X}v$$

where $\beta = \frac{v}{V}$.

Figure 1.- Variable-stability helicopter. L-63-8407

DESCRIPTION OF TASKS

Instrument Flight Task

Hooded instrument approaches on a standard 3° instrument low-approach system (ILAS) provided the primary task for evaluation of the aircraft handling characteristics. The evaluation pilot took command of the aircraft 4 miles from the runway threshold on a 90° heading with respect to the localizer. Upon intercepting the localizer, the pilot turned inbound and held constant altitude until interception of the glide slope. Beyond this point the pilot endeavored to maintain a constant speed of 45 knots while keeping the localizer and glide slope needles centered.

Visual Flight Task

In order to test the generality of the aforementioned instrument (IFR) results for visual (VFR) conditions and to provide a realistic task which would define the directional control sensitivity requirements more specifically, the following VFR task was selected. While holding a speed of 30 to 35 knots, the evaluation pilot made descending approaches on runway heading, but with an intentional misalinement of about 300 feet. At a distance of 300 feet from the runway threshold the pilot commenced a rapid S-turn maneuver so as to aline the aircraft with the runway center line. Although an actual touchdown was not performed, the pilot executed all the maneuvers required for touchdown including elimination of crab angle.

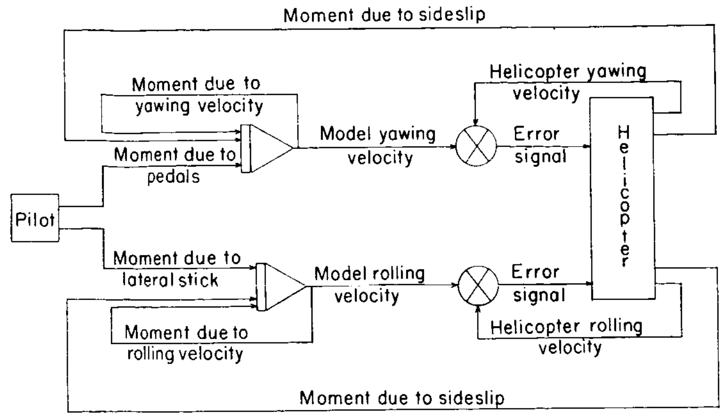

Figure 2.- Signal flow diagram of simulation.

RESULTS AND DISCUSSION

General

In general, a consideration of directional handling qualities must include a knowledge of the lateral characteristics of the aircraft since coupling generally exists between the lateral and directional axes. A normally desirable aspect of the coupling which is produced by static directional stability is that the aircraft heading tends to follow laterally initiated turns without the use of pedals. The extent to which this turning response is achieved is a function of the level of static directional stability and directional damping. An undesirable aspect of the coupling that is produced by dihedral effect results in excitation of the Dutch roll oscillatory mode for certain combinations of directional and lateral characteristics.

In order to provide a summary of pertinent parameters for each axis, the parameters and the ranges covered are indicated as follows:

Parameter	Range
M_{Z_δ}/I_Z	0.1 to 0.3
M_{Z_r}/I_Z	0 to -2.0
M_{Z_β}/I_Z	0 to 1.0
M_{X_δ}/I_X	0.4
M_{X_p}/I_X	-1.5

Parameter	Range
M_{X_v}/I_X	0 and -0.014
M_{Y_δ}/I_Y	0.3
M_{Y_q}/I_Y	-4.0
M_{Y_u}/I_Y	Slightly stable
M_{Y_α}/I_Y	Slightly stable

The directional handling characteristics provided by each combination of parameters were rated by use of the pilot-rating system shown in table I and described in reference 5.

Instrument Flight Results

Static directional stability, damping, and sensitivity.- Although several combinations of static directional stability and damping were evaluated for values of sensitivity ranging from 0.1 to 0.3 $\frac{\text{radian/sec}^2}{\text{in.}}$, it was readily apparent that these variations in sensitivity had no significant effect on the overall pilot rating except for low values of static stability. (The importance of sensitivity will be made apparent, however, in a subsequent section.) At low static stability some improvement was noted with increased sensitivity. In figure 3, pilot-opinion boundaries are mapped for directional damping as a function of static directional stability. These boundaries were derived from analysis of commentary and ratings assigned by the project pilot as presented in the appendix in addition to results obtained from the other test subjects. These tests were run at a moderately stable level of dihedral effect $\left(\frac{M_{X_v}}{I_X} = -0.014 \frac{\text{radian/sec}^2}{\text{ft/sec}}\right)$ and at a directional sensitivity of 0.2 $\frac{\text{radian/sec}^2}{\text{in.}}$, which corresponds to the minimum sensitivity requirement of reference 2.

For a nominal speed of 45 knots, figure 3 indicates that a minimum static stability of about 0.3 $\frac{\text{radian/sec}^2}{\text{radian}}$ is required to provide satisfactory handling characteristics. When the level of static stability was below 0.3 $\frac{\text{radian/sec}^2}{\text{radian}}$, the aircraft heading tended to wander aimlessly and required a deliberate effort to execute coordinated heading corrections. It was for those low values of static stability that the pilot appreciated increased sensitivity to aid in making heading correction during the approach. As the static stability and damping were increased simultaneously along the line of "optimum ratio" (fig. 3), the handling characteristics continued to improve. For combinations above the optimum ratio line, the characteristics were downrated because of sluggishness of the aircraft in following stick-initiated turns. Below the optimum ratio line, the characteristics deteriorated as a result of Dutch roll oscillatory characteristics which accompanied greatly reduced damping values.

Analysis of the data indicates that the optimum ratio line (fig. 3) lies between damping ratio ζ values of 0.8 and 1.0 (on a single-degree-of-freedom basis as opposed to the coupled mode). In order to illustrate this trend further, pilot ratings and damping ratios ζ are plotted in figure 4. Damping ratios for the uncoupled directional mode were computed for test combinations having a static stability equal to or greater than $0.4\ \frac{\text{radian/sec}^2}{\text{radian}}$. The figure clearly indicates the rate of improvement as critical damping is approached (damping ratio equal to unity). The single-degree-of-freedom damping ratio is important even in the presence of Dutch roll coupling, apparently because the pilot controls the aircraft so as to reduce the roll due to sideslip, thus partially decoupling the Dutch roll mode. Also, damping ratio is a measure of the aircraft response to external disturbance in yaw.

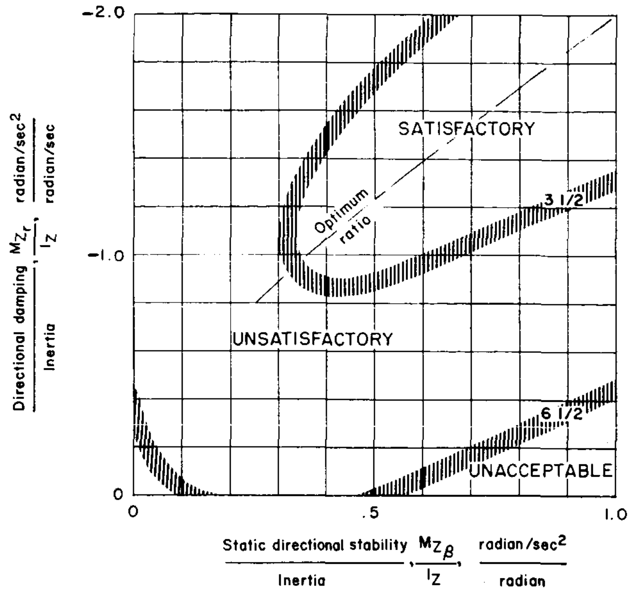

Figure 3.- Pilot rating boundaries of static directional stability and directional damping $\left(\text{directional sensitivity} = 0.2\ \frac{\text{radian/sec}^2}{\text{in.}}\right.$ and dihedral effect $= -0.014\ \left.\frac{\text{radian/sec}^2}{\text{ft/sec}}\right)$.

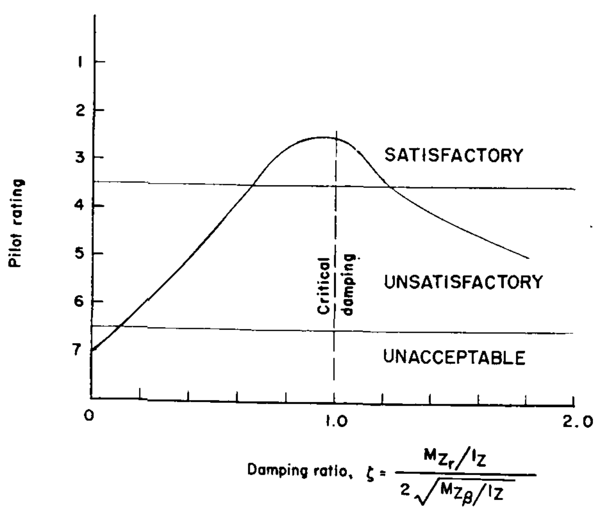

Figure 4.- Effect of damping ratio on directional handling qualities for $\frac{M_{Z_\beta}}{I_Z} \geqq 0.4\ \frac{\text{radian/sec}^2}{\text{radian}}$.

Wind conditions encountered during the testing included wind from all directions relative to the flight path and ranged from 5 knots or less to 15 knots with occasional gusts to 25 knots. The high gust responsiveness associated with high values of static stability did not impair the pilot's ability to control heading when sufficient damping was present to provide a damping ratio of 0.6 or greater - a rough ride was the only detrimental effect. For damping ratios of 0.6 or greater and the type of disturbances experienced, the gust produced only transient heading changes which did not require corrective pilot

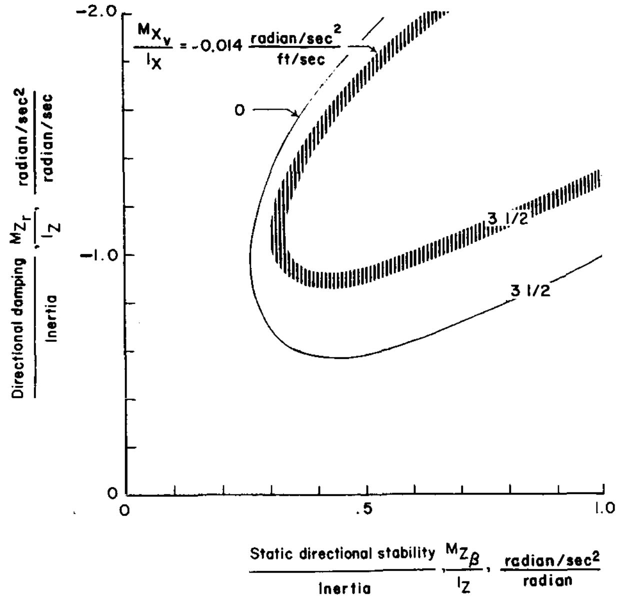

Figure 5.- Effect of dihedral on directional damping as a function of static stability boundaries for IFR operation.

action since the aircraft would return rapidly to its original heading following a disturbance.

Dihedral effect.- A number of test conditions were reevaluated with zero dihedral effect to indicate its effect on directional handling characteristics. In figure 5, the boundary for a pilot rating of $3\frac{1}{2}$ which was obtained at zero dihedral effect is compared with the $3\frac{1}{2}$ boundary which was obtained with high dihedral effect (from fig. 3). (For rating system, see table I.) The results indicate a general improvement with reduced dihedral effect. Pilot comments attributed the improvement to two factors: First, there was a reduction in lateral disturbances which significantly reduced the pilot workload and secondly, the Dutch roll tendency was completely eliminated, so that lower directional damping could be tolerated for a given amount of static stability. Although oscillatory characteristics about the yaw axis still existed for very low values of directional damping, the oscillations were less objectionable because in the absence of dihedral effect, the oscillations were uncoupled from the roll axis so that turning of the flight path did not result; the oscillations were of longer period and were better damped.

Compatibility of IFR Results for VFR Operation

In order to determine the extent to which the IFR results were compatible for VFR operation, selected combinations of static stability and damping were reevaluated for the VFR task which is described in a preceding section. Inasmuch as initial results obtained for the VFR task indicated that dihedral effect had a negligible influence on pilot rating for the VFR task, the level of dihedral effect was subsequently held constant (at zero).

During the VFR testing, directional sensitivity emerged as a significant parameter, as indicated by figure 6, which is a plot of pilot rating against damping ratio for three values of sensitivity. The results presented in figure 6 were obtained in the presence of crosswinds of about 10 knots with gusts to 15 knots. The figure indicates that a minimum directional sensitivity of about 0.25 $\frac{\text{radian/sec}^2}{\text{in.}}$ is required to insure satisfactory control even with optimized values of static stability and damping. Pilot commentary indicated that the required directional sensitivity was essentially independent of static directional stability within the range investigated. This fact was apparently due to conflicting requirements for sensitivity. For high values of static directional stability, the minimum sensitivity was dictated by the amount required to trim in a crosswind. When the static directional stability was reduced, a new requirement based on maneuvering arose as a result of a reduction in the inherent turn-following characteristic. These requirements offset each other to the extent that the resulting sensitivity requirement was essentially independent of static stability for the range investigated.

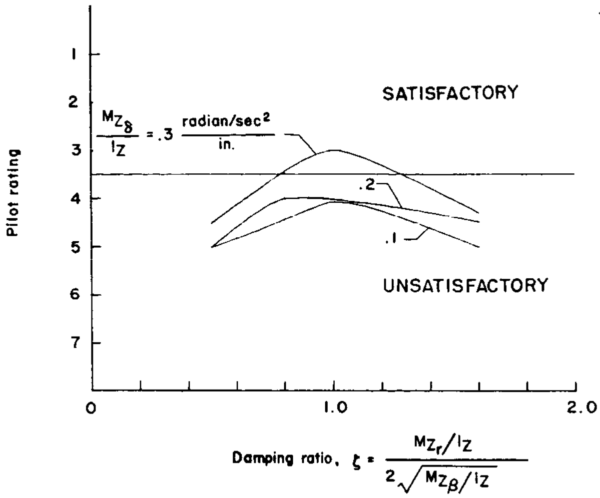

Figure 6.- Effect of directional sensitivity on directional handling characteristics for VFR operation.

The fact that the importance of directional sensitivity was brought out during VFR and not IFR flying reflects the difference in the tasks used in this investigation. For example, it was not feasible to extend the instrument approach down to an actual landing on instruments. It should be assumed, however, that in practice the importance of achieving the minimum sensitivity indicated would be greater for zero-visibility landings than for visual operation.

The lack of pilot appreciation for reduced levels of dihedral effect under VFR conditions was attributed to the fact that, through the use of visual cues, the pilot readily eliminated roll due to sideslip. This is contrary to the results obtained for the IFR tasks where the pilot must deduce roll attitude and sideslip condition from his instrumentation, thereby delaying corrective action.

A comparison of the results obtained for the IFR and VFR tasks is presented in figure 7, which is a replot of the results presented in figures 4 and 6. The figure clearly illustrates a similar trend for both tasks. The tendency of all the curves to peak near the same value of damping ratio indicates that the same combinations of static stability and damping were found desirable for both tasks. Also, the lower slopes obtained for the VFR curves than for the IFR curve illustrate a well-known fact, namely, that the pilot is less sensitive to changes in aircraft stability under visual conditions. On the basis of the results presented in

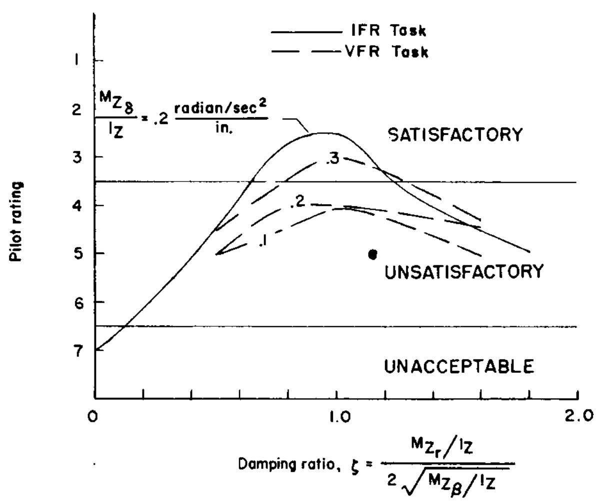

Figure 7.- Comparison of IFR and VFR results.

this section, it appears reasonable to conclude that the results obtained under IFR conditions are compatible for VFR operation.

CONCLUSIONS

Flight tests with a variable-stability helicopter were conducted at low speeds (excluding hovering) in the presence of wind conditions ranging from calm to moderately turbulent. The effects of gross changes in static directional stability were evaluated for various combinations of directional sensitivity and damping for both an IFR and a VFR task. On the basis of the results obtained from this investigation, the following conclusions are drawn for the above conditions:

1. Increases in static directional stability, when accompanied by appropriate increases in directional damping, result in improved handling qualities. A minimum static directional stability of $0.3 \frac{\text{radian/sec}^2}{\text{radian}}$ is required to insure satisfactory control response for the parameters investigated.

2. Minimum satisfactory directional sensitivity and damping are in agreement with current criteria.

3. For optimization of characteristics for a given amount of static directional stability $\left(\text{static stability above } 0.3 \frac{\text{radian/sec}^2}{\text{radian}}\right)$, sufficient directional damping should be provided to yield a damping ratio between 0.8 and unity.

4. For the instrument task, reduction of dihedral effect resulted in improved lateral-directional handling qualities due to a reduction both in external lateral disturbances and Dutch roll oscillatory tendencies; for the visual task, the pilot was insensitive to changes in dihedral effect.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 19, 1964.

APPENDIX

METHOD OF ANALYSIS USED FOR DEDUCING THE PILOT OPINION BOUNDARIES OF FIGURE 3

The commentary and ratings assigned by the project pilot to each of the test combinations indicated in figure 8 are presented in table II. The indicated ratings were obtained at a directional sensitivity of 0.2 $\frac{\text{radian/sec}^2}{\text{in.}}$ and a dihedral effect of -0.014 $\frac{\text{radian/sec}^2}{\text{ft/sec}}$ and provided the primary basis for figure 3 in the text.

In an effort to determine whether a single parameter existed which could be correlated with pilot ratings, various combinations of static directional stability and directional damping were combined into a single parameter and plotted against pilot rating. Of all the combinations tried, the only one which appeared to yield any correlation was given by the relation $\frac{\left(M_{Z_r}/I_Z\right)^2}{M_{Z_\beta}/I_Z}$, which is recognized as merely $4\zeta^2$ where ζ represents the commonly defined damping ratio. A plot of pilot rating against damping ratio is shown in figure 4 for values of $\frac{M_{Z_\beta}}{I_Z} \gtrsim 0.4 \ \frac{\text{radian/sec}^2}{\text{radian}}$ (for values of static directional stability appreciably below this value, the damping ratio appears to have no bearing on handling qualities). It is apparent from inspection of figure 4 that a fairly well-defined relationship exists between pilot rating and damping ratio for the range of parameters under consideration. From figure 4, therefore, it appears reasonable that combinations of static directional stability and damping which yield a damping ratio of about 0.65 should correspond to a pilot rating of $3\frac{1}{2}$. Similarly, the other half of the $3\frac{1}{2}$ boundary should be represented approximately by a damping ratio of 1.2.

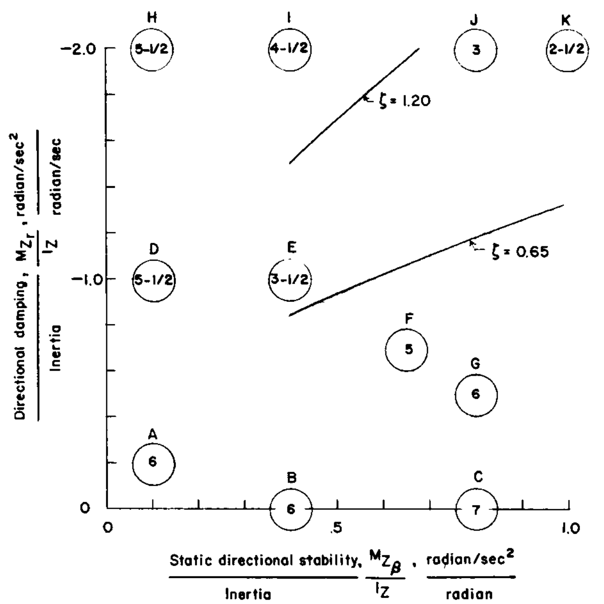

Figure 8.- Correlation of pilot ratings for various combinations of static directional stability and directional damping with damping ratio values from figure 4. (See tables I and II.)

In figure 8 are shown the pilot ratings for various combinations of directional damping and static directional stability in addition to lines of constant damping ratio for $\zeta = 1.20$ and $\zeta = 0.65$. This figure indicates the extent to which constant damping ratio lines correlate the existing data points and also implies the extent to which lines of constant damping ratio may be relied upon for extrapolation of pilot-rating boundaries into untested areas. On the basis of the preceding considerations, the pilot-opinion boundaries of figure 3 were mapped.

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TABLE I.- PILOT-OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

TABLE II.- SUMMARY OF RATINGS AND COMMENTS FROM PROJECT PILOT FOR RESULTS PRESENTED IN FIGURE 3

Condition (from fig. 8)	$\frac{M_{Z_\beta}}{I_Z}$, $\frac{\text{radians/sec}^2}{\text{radian}}$	$\frac{M_{Z_r}}{I_Z}$, $\frac{\text{radians/sec}^2}{\text{radian/sec}}$	Pilot rating	Pilot comment
A	0.1	-0.2	6	Aircraft turning does not follow bank soon enough. Pedals are required for damping disturbances or starting and stopping turns. Consequently, both bank attitude and turn needle have to be used for control. No oscillation problem, as such, exists.
B	0.4	0	6	Very poor characteristics. Large-amplitude oscillation of long period. Difficult heading control. Damping too low for level of static directional stability provided.
C	0.8	0	7	Intolerable characteristics. Violently oscillatory.
D	0.1	-1.0	$5\frac{1}{2}$	Aircraft will not follow into desired turns using lateral control.
E	0.4	-1.0	$3\frac{1}{2}$	Some problem turning. No oscillations. Pedals required to control heading reasonably.
F	0.65	-0.7	5	When disturbed, aircraft makes several swings of large amplitude and low period. Finally, pedals required to stop swings and control heading with accuracy.
G	0.8	-0.5	6	Most unsatisfactory characteristics. Motion very oscillatory and period long enough so that turn and swings must be controlled with pedals in addition to bank.
H	0.1	-2.0	$5\frac{1}{2}$	Aircraft will not follow into desired turns using lateral control.
I	0.4	-2.0	$4\frac{1}{2}$	Somewhat too much damping for turning. However, turning better than for condition B because no oscillation was present.
J	0.8	-2.0	3	Overall turn following is good; however, initial turn entry is somewhat sluggish due to high damping.
K	1.0	-2.0	$2\frac{1}{2}$	Good turning response to bank. A little residual sideslip in turns due to high damping, but could be ignored. No oscillations.